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Teaching for numeracy and mathematics transfer in tertiary science

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Contents

Summary

This project aimed to identify and implement pedagogical strategies designed to facilitate the transfer of numeracy and mathematical skills and knowledge to science disciplines. To achieve this aim a review of the literature was conducted that yielded numerous teaching and learning strategies for successful transfer of knowledge across contexts with potential to use in the sciences. Six strategies were chosen by lecturers and academic developers for field testing in science courses because they met three main criteria: 1) they were relevant to the course context; 2) they were practical and accessible to lecturers; and 3) they were effective in helping students see the connections between mathematics and science.

Background

This project has its origins in late 2011 when several academics from the School of Biological Sciences and the Department of Chemistry at the University of Canterbury expressed their concerns to the Dean of Science (Prof Wendy Lawson) about students' poor mathematical preparation and numeracy skills in introductory courses. In response to these concerns the Dean established the Numeracy Working Group[1], to determine the mathematical background of Bachelor of Science (BSc) students at the university, using students in Chemistry as a case study. To assist in this information gathering, the Dean asked the University's Academic Development Group to conduct an initial investigation on the topic. In this initial study, the Numeracy Working Group and the Academic Development Group worked collaboratively to find that:

1) On paper students have sufficient background to deal with the numeracy and mathematics required in the courses. This background was either in the form of secondary school preparation through National Certificate of Educational Achievement (NCEA) level 3 credits in Mathematics with Calculus or Statistics and Modelling, or through previous or concurrent enrolment in mathematics, statistics or engineering mathematics courses at University (Sampson & Brogt, 2011; Brogt, 2012).
2) Chemistry academics concurred that students' background (above) adequately prepared them for the mathematics required in the first year courses.
3) Despite students being prepared 'on paper' they seemed to struggle to apply the mathematical knowledge and skills in biology and chemistry courses. Course content and concepts covered in the secondary school curriculum and NCEA programme, were difficult for students to utilise within a tertiary science context.
4) Anecdotal evidence from other departments in the Science Faculty, in particular the Department of Physics and Astronomy, suggested that students across year levels were observed to struggle to apply previously learnt mathematics in Science courses.

[1] There has been some contention among members of Faculty with regards to the use of the terms "numeracy" and "mathematics", with "numeracy" being seen as too elementary and "mathematics" as too advanced. The knowledge and skills deal with a wide variety of concepts, from working with fractions, via balancing equations to elements from calculus such as logarithms and complex e-powers. Throughout this report, we have used the combined terminology numeracy and mathematics to reflect this broad range.

These findings suggested a problem of transfer - the ability to take what is learnt in one context and successfully apply it in another - rather than a lack of mathematical knowledge or preparation. The findings were discussed at a Faculty of Science meeting, and colleagues from the Department of Psychology concurred with the working hypothesis that the issue should be approached as a problem of transfer, an area that receives considerable attention in cognitive psychology. Based on the significance of the findings to mathematics teaching and learning, the Faculty, backed by the Dean of Science and the Pro-Vice-Chancellor, asked the working group to undertake further investigation. The working group decided to focus research around approaches to teaching and pedagogy that assist students with transfer, and approached Ako Aotearoa for financial support. In November 2012, Ako Aotearoa agreed to fund a Regional Hub Funding Proposal to investigate the transfer of mathematical skill and knowledge into tertiary science teaching.

Method and Design

The project was divided into two phases:

- The first phase consisted of a review of existing literature around transfer to locate possible strategies for what is referred to as "teaching for transfer". Specifically, we aimed to identify practical teaching techniques and pedagogical strategies that science and engineering lecturers could employ to promote transfer of mathematical skills and knowledge across disciplinary domains at the tertiary level.
- The second phase ran over two semesters and consisted of a) piloting the teaching techniques in the classroom, and b) evaluating and adapting the techniques for further testing.

Carl Wieman Science Education Initiative

The project followed a variant method advocated by the Carl Wieman Science Education Initiative (www.cwsei.ubc.ca) that was used in the Ako Aotearoa commissioned and funded project *Transforming Tertiary Science Education* (Kennedy et al., 2013).

Research sites

The Department of Chemistry volunteered to act as a research site, and two courses were selected for investigation over two semesters in 2013:

- Semester 1 - CHEM114 *Foundations of Chemistry*, a first year general introduction course.
- Semester 2 - CHEM243 Molecules and Reactions, a second-year physical chemistry course (arguably the most mathematical branch of chemistry).

Dr Sarah Masters, the course lecturer worked closely with the university's academic developer (Dr Erik Brogt) and the project's research assistant (Dr Annie Soutter) to translate the ideas from the literature into pedagogical practice.

Both courses are discussed in more detail below.

CHEM114: Foundations of Chemistry is a preparatory course in chemistry and serves three main target audiences:

- Students who wish to major in chemistry but do not meet the entrance criteria for the first-year major courses CHEM111[2] and CHEM112[3], [4].The course aims to give students the necessary chemistry background and knowledge to successfully cope with the major courses.
- First-year forestry students, for whom CHEM114 is the recommended chemistry course to fulfil their chemistry requirement.
- Biology students who would like to keep the option open to major in biochemistry, but do not meet the entrance requirements for CHEM111 and CHEM112.

CHEM114 assumes minimal preparation in chemistry, and emphasises the properties of materials and biological systems. The course content includes sections about atoms, molecules, the mole concept, chemical equations, stoichiometry, electron configuration, bonding, molecular structure, energy changes and kinetic factors in chemical reactions, aqueous chemistry and introductory organic chemistry. No mathematical background is assumed or required, and as a result the level of mathematical content or sophistication in the course is not high. However, by the end of the course students are expected to put into practise basic algebraic skills, and are required to be able to balance, rearrange, and manipulate simple physical chemistry equations.

CHEM243: Molecules and Reactions is the keystone 200-level physical chemistry course. It provides a deeper foundation in physical chemistry upon which the 300-level physical chemistry courses are built, thus serving as an important prerequisite. The curriculum of CHEM243 deals with the science of the very small and includes topics on quantum theory, statistical mechanics as well as thermodynamics and kinetics. Students taking CHEM243 range across disciplinary majors, for example:

- Chemistry (most common)
- Engineering, in particular, chemical and process engineering students who need to take a 15 point course to complete their degree.
- Physics, most of whom will have completed or will be concurrently enrolled in an introductory course in quantum physics, PHYS203[5].

The latter two cohorts (engineering and physics students) will have completed the introductory chemistry course for majors, CHEM111, and an introductory physics course, PHYS101[6].

The mathematics needed for the CHEM243 involves rearranging equations, integration and differentiation, the use of boundary conditions to generate a unique solution from a general case, some Taylor series, complex e-powers, and the Schrödinger equation.

The engineering and physics students are on paper generally very well prepared mathematically and are aware that doing a course in physical chemistry will involve mathematics. The chemistry students on the other hand, while prepared on paper, are often less prepared and much more likely to struggle with the mathematical content, with or without a transfer issue. From prior experience in the classroom, it was clear that students were not comfortable with the derivations of the equations, in

[2] CHEM111 - Chemical Principles and Processes
[3] CHEM112 - Structure and Reactivity
[4] In 2013 9 credits in chemistry at NCEA level 3, changing to 14 credits in 2014
[5] CHEM203 - Relativistic and Quantum Physics
[6] PHYS203 - Engineering Physics A: Mechanics, Waves and Thermal Physics

particular when derivatives and wave functions were involved (as they do in solving the Schrödinger equation).

Literature Review

An extensive literature base exists on the transfer of numeracy and mathematical skills and concepts to other domains, and has been an active area of research for many years, going back to Thorndike at the beginning of last century (see e.g. Bransford, Brown & Cocking, 2000, or Rebello et al., 2004). However, the literature often sits in specialised educational (psychology) journals, which are not commonly read by academic outside that particular research field. The nature of scholarly literature also means that it is not commonly translated into concrete actions that individual lecturers can take to help students transfer numeracy and mathematical skills and knowledge studied in one particular course across domains. In addition, most of the work done in this area pertains to the primary and secondary arena, not tertiary education (e.g. Jones, Jones & Vermette, 2009). To complicate matters further, quantifying transfer is a non-trivial task, though some work in this area is quite promising (see e.g. Roberts, Sharma, Britton & New, 2007).

For this project, we reviewed recent scholarship on cross-disciplinary or inter-domain transfer of learning from mathematics, and describe the general trends. We begin by situating recent theoretical and empirical work in relation to the perspective that underpinned much of the work on transfer in the fields of education and psychology. Second we describe some methodological approaches that have been utilised to examine transfer from these emerging points of view. Last, we provide a brief synopsis of some of the pedagogical strategies proposed to support transfer of mathematical learning to other disciplines and to the “real world.”

Teaching for transfer in some ways seems like a redundant phrase. In some respects, understanding what has been researched and written about teaching for transfer is, in itself, not much different than exploring the evidence available for good pedagogy. Learning involves not simply ‘knowing’, but also the ability to use and apply what has been learned at some point or place in the near or distant future. However, there is an assumed contrastive element involved to distinguish learning from transfer; learning involves demonstration of what has been learned, transfer involves the added condition that learning can be used in a different context from that in which something has been learned (Perkins & Salomom, 1992). While transfer certainly involves extrapolating learning to situations to familiar (albeit different) contexts, transfer to novel contexts is also necessary in many learning situations. What stands out in the recent literature emanating from the fields of cognition and education in general, and specific subject disciplines such as mathematics or sciences in particular, is that that transfer is a complex, multi-dimensional and hard to define construct.

Consider a common point of departure for contemporary scholarship on transfer. Out-dated theories of learning (classical behaviourism in particular) and the metaphors they represent (that a fixed, “known” form of knowledge can be “transported” from one context to another) fail to address the complexity of teaching and learning. On the last point, Perkins and Salomon (1992) distinguish between two means by which transfer may occur. Reflexive (i.e. low road) transfer occurs when well-practiced routines are triggered by stimulus conditions that resemble those in the learning context (ibid.). In contrast, mindful (i.e. high road) requires deliberate and effortful abstraction and attempts to identify connections on the part of the learner (ibid.). According to Perkins and Salomon (Perkins & Salomom, 1992) typical classroom environments foster neither mindful nor reflexive transfer.

One condition recognised by many contemporary scholars as hindering successful transfer relates to the extent to which the learning environment is acknowledged as complex and in dynamic interaction with the learners within it. For example, recent scholarship reflects attention to how learners bring with them prior experiences, assumptions (correct or not), mathematical meanings (Boaler, 1993; Evans, 1999), their identities as learners (Gee, 2000; Wenger, 1998) and their motivations (see Ames, 1992; Dweck, 1986), that impact on how the material is learned or utilised. As an aside, an interesting issue was presented by Bassok & Holyoak (1989) who showed that students could transfer knowledge from algebra to physics, but not from physics to algebra. Since their article, many theorists have addressed issues that may explain this. Some have argued, for instance, that, students' may expect mathematics to apply broadly. It is not uncommon for mathematics to be viewed as a foundational discipline, one that can be generalised to other disciplines, physics less so. These perspectives bring to light the role of expectancies in transfer.

Many contemporary theorists reject the strongly cognitive perspective of learning (a la Thorndike, 1906, for example) that many take to imply that knowledge is relatively stable, can be generalised to different situations, and transportable (see Greeno, 1997; Lave, 1993; Lobato, 2006b; Scribner & Cole, 1981). Perspectives with more traction in education today include situational- (see Boaler, 1993; Carraher & Schliemann, 2002; Lave & Wenger, 1991), actor-oriented (see Lobato et al., 1993, Lobato, 2006); boundary-crossing (see Davis & Sumara, 2006; Frade, Winbourne, & Braga, 2009) or post-structuralist 'translation' or 'meaning making' (Evans, 1999) points of view, perspectives that require a broader methodological approach. New research methodologies include a metrics for exploring whether students are actually transferring mathematics to other disciplines (Britton, 2006; Britton et al., 2005), as well as multi-methods studies. In particular, qualitative data is increasingly being used to illuminate the cognitive resources and processes such as student expectations and literacy skills (Roberts et al., 2009) or to better understand learner's perspectives on transfers and the relationship between their 'internal knowledge' and the context (Boaler, 1993; Wagner, 2006). Evans (1999) argues that such approaches can bring attention to the 'signs' and 'signifiers' may point to "fruitful" areas of 'inter-contextuality' and an opportunity to show where school mathematics and other domains share common and workable ground.

Many contemporary scholars propose that transfer work needs to reflect a more learner-centred pedagogical approach (making space for learners to engage in the meta-cognitive work necessary for them to bring to light what they know about the subject, how they are to engage with it, what its purpose is, the ways in which it is meaningful to them as individuals, etc. (Lobato, 2006a, 2006b, 2012; Lobato, Rhodehamel, & Hohensee, 2012). In our opinion, this is an important first step leading to the key pedagogical element for better utilisation of mathematical material in non-maths courses – the effective use of feedback (see Baker, Gersten, & Lee, 2002; Hattie, 2009)**.** The meta-cognitive work on the part of the learner serves to *inform* the educator's curriculum development so she/he builds upon these bits of prior knowledge, understandings (or misunderstandings), and internalised skill sets and use them to frame learning experiences (i.e. establish a learning context that is familiar, meaningful, and clearly related to other, perhaps even different contexts).

Effective use of feedback depends on consistently gauging what students already know/can do and involves three questions: "*Where am I going?*" (learning intentions/goals/success criteria), "*How am I going?*" (self-assessment and selfevaluation), and “*Where to next?*” (progression, new goals) (Hattie, 2009, p. 177). Feedback may reveal what Hoban et al. (Hoban, Finlayson, & Nolan, 2013) and (Potgieter, Harding, & Engelbrecht, 2008) found in their studies, that students’ prior mathematical knowledge/skills were insufficient to engage with the work in a different subject (e.g. poor graphical representation or analysis skills). This is particularly important to consider if one accepts O’Byrne and colleague’s (O'Byrne, Britton, George, Franklin, & Frey, 2009) argument that a commonly used predictor of success – high school performance, did not accurately predict students at risk of failing in first-year science courses), nor did in-class assessments given in the first half of the course.

In other cases, the mathematical preparation proved adequate for the tasks, but students appeared to be coming at new problems from a different perspective than the instructor had expected or framed them. This may be compounded by the lack of attempt on the educator’s part to explore where students are coming from, or how they are viewing the problem, or what they are ‘noticing’ about the features of the task or context (Lobato, et al., 2012). Consequently, in many situations, the students’ work is marked incorrect – the situation described as an “inability to transfer”, although it may in fact be simply reflecting the reality that students were presenting their results in ways that did not align with the educators' approach. Beneath the surface of their final answer, their rationale and approach may suggest a much more nuanced understanding of the properties, structure and possibilities of mathematical knowledge. Mathematical meaning is complex, multi-dimensional and dynamic in the ‘real world’.

Another challenge to success in new arenas has to do with students’ cognitive load, which may be compromising their ability to critically analyse what is going on. For example, students may be reliant on previously learned mathematical strategies that are no longer applicable in the novel learning context. Additionally, stress, multiple papers within a semester, extra-curricular activities, employment, or family responsibilities may compete with the attention and thinking space for students leading to, among other things, difficulties in tapping into long term memory (Redish, 2003; Roberts, Sharma, Britton, & New, 2009) or abstracting and exploring other possible connections (Perkins & Salomom, 1992).

Specific strategies to facilitate transfer

The review yielded several articles that describe specific pedagogical strategies that draw upon information gained from feedback and attempt to address some of the theoretically and empirically identified hindrances to ‘transfer.’ These include those that reduce cognitive load, emphasise the purpose and value of the mathematical material for the new situation, and meet students where they are at. Most meet Perkins & Salomon’s (Perkins & Salomom, 1992) following conditions for transfer:

- Thorough and diverse practice (Luria, 1976; Scribner & Cole, 1981)
- Explicit abstraction (see Gick & Holyoak, 1983; Gick & Holyoak, 1980)
- Active self-monitoring (metacognitive reflection)
- Mindfulness to activities and surroundings
- Use of metaphor or analogy

To this list, we can add a few others observed in the literature as conditions conducive to transfer:

- Minimize cognitive load (through learning aids or focused attention)

- Emphasis on the value and of the learning material and its potential purpose for different contexts/disciplines
- Meet students where they are at (by identifying prior knowledge, assumptions, aims for their learning, intentions for use of the material learned and designing curriculum that suits)

General strategies to facilitate transfer

Below, in no particular order, we list several general teaching strategies identified in the literature as helpful for facilitating transfer:

- Student-generated data or examples (Bernardo, 2001; Woolnough, 2000)
- Analogical model formulation (Klenk & Forbus, 2009) in which scenario models of everyday situations are built, based on prior experience; cooperative learning (Kramarski, 2004)
- Peer instruction (Mazur, 1997)
- Using simulations that are characterised by varied appearances (Gick & Holyoak, 1983; Gick & Holyoak, 1980; Goldstone & Son, 2005) and progressive idealization of simulations, or "concreteness fading" (Goldstone & Son, 2005) to address their empirical findings that instruction leading to best immediate performance is not always the same as instruction preparing learners for future learning opportunities (see also (see also Bransford & Schwartz, 1999)
- Self-verbalisation and prediction (see De Bruin, Rikers, & Schmidt, 2007)
- Worked examples in which the instructor leads students through from problem identification to solution(s) in a step-by-step manner (Atkinson, Derry, Renkl, & Wortham, 2000; Große & Renkl, 2007)
- *Hugging*, where the learning experience closely matches the application of the learnt material, and *Bridging*, where connections are made between the material and other applications (Perkins & Salomom, 1988)

University-based centres for teaching and learning around the world have developed and employed tools and strategies to support learning and transfer as well. Many of these put teaching for transfer in a broader context of best practices around the development of good learning goals, and curriculum and assessment design for face-to-face, online, and blended learning environments. Programmes such as those at Stanford University, University of Oregon, University of Virginia, and University of Michigan may provide teaching staff with useful tools and ideas to assist them with their practice.

Testing the Teaching Strategies

The first round of implementation – CHEM114 Semester One

Based on the literature reviewed above, and mindful of the properties of the target population, Sarah opted to use several of the suggested strategies for building capacity for sustained change for learners in her teaching of CHEM114. These include:

- Setting clear expectations for what is to be learned, and clearly identify what students will be held accountable for.
- Using worked examples to illustrate how chemistry concepts mirror and/or translate from other known mathematical problems.

- Bridging conceptually between what students know/are coming to know and other applications within and outside of chemistry; clearly verbalising links to prior knowledge and how the current material will be linked and be relevant to future lectures and classes.
- Using analogies to tie content to daily-life experiences of the students.

The number of strategies was deliberately kept to a minimum for two reasons:

1) The amount of numeracy and mathematics is relatively limited in CHEM114 and the opportunity to try out strategies was limited. By only focusing on a few strategies, Sarah was better able to practice them.
2) It is a commonly accepted view within academic development that evolution is more likely to lead to sustained changes in practice than a full-blown fundamental overhaul. Teaching has to happen within the instructor's comfort zone, and pushing too far, too fast is likely to be counterproductive and not sustained beyond the timeframe of the project.

Sarah's lectures and some problem-sessions were observed on a regular basis by the project researcher, Annie, who provided feedback and suggestions. This feedback was not limited to facilitating transfer, but also involved general pedagogical strategies.

Sarah's lectures were designed to enable the students to clearly see what was expected of them within that lecture timeframe. Lectures were broken down into smaller sections with breakout sessions to enable students to gauge their immediate learning against a series of relevant questions. Problem-solving sessions were structured to enable peer-assisted learning for a large class setting. Students were encouraged to ask questions during lectures to ensure immediate understanding and eliminate lingering confusion about any concepts. More complex concepts were presented in several ways, and repeated over several lectures to ensure understanding. Iterative changes were made as the teaching progressed based on classroom observations and subsequent pedagogical feedback by Annie. For example, Annie was able to observe the student reaction to introduced concepts and gauge the level of understanding simply by observing body language. This is hard for a lecturer to do in large lecture situations. In response to this feedback the structure of a subsequent lecture was changed to incorporate material to clarify concepts and more complicated material was removed. The problem-solving sessions were also structured around the feedback received from both the students and Annie regarding their understanding of concepts introduced that week. The students were given ample opportunity to practise the numeracy and mathematical aspects of the course, both during the lecture with breakout, peer-directed learning style, sessions, and during the problem-solving sessions at the end of a topic.

Results indicate that students generally have a good grasp of the material and performed well in the test given to them halfway through the semester. The test covered all of Sarah's material and half of the next lecturer’s material. Students also engaged with the material, sending Sarah many links to online learning sites as suggestions so that subsequent classes may benefit from the experiences of the current cohort. They also engaged in the laboratory setting, relating the laboratory experiments to the material presented in lectures. In addition, most of the students coped well with the mathematical questions in the test with ~95% of them returning the correct answers to the mathematical questions relating to Sarah’s material.

Sarah's end-of-semester course evaluation scores showed a substantial increase from the previous year for a similar 100-level course (i.e. from 3.1/5 to 4.4/5). Sarah noted that she subsequently revised her teaching style to be more student-centred and is much more aware of how students perceive the material. One reflection offered by Sarah was her recognition of how one can easily forget that the lecture setting is students' first exposure to the material being taught. Therefore, they take more time to absorb information that may appear trivial to others with more experience.

The second round of implementation – CHEM243, Semester Two

In the second semester of 2013, Sarah taught part of the second year physical chemistry course, CHEM243. Erik observed most of Sarah's lectures and provided feedback and suggestions afterward. As in the first semester, feedback was not limited to areas related to transfer of numeracy and mathematics, but involved general pedagogy as well.

In addition to the four strategies employed in the first semester, Sarah also used the following two strategies in her teaching:

1) Verbalising while writing on the board to provide access to students with various styles of learning (see e.g. Hawk & Shah, 2007)
2) Student interactions and discussions; encouraging students to reflect on the process and outcomes (see e.g. Fogarty, Perkins, and Barell, 1992)

These strategies were added for the following reasons:

- CHEM243 is a much smaller cohort and without large classroom management overheads student-student and student-instructor interactions are more likely to be fruitful.
- The mathematical material in the course is reasonably complex and provided more examples where students' required help to a) understand the mathematical material and b) facilitate transfer from mathematics to chemistry by using examples with a strong applied focus.
- The complexity of the mathematics means that correct notation becomes increasingly important. Verbalising what is written on the board minimises the chance that notational errors will occur, both from students and from the instructor.

Sarah's section of the course focussed on the application of quantum mechanics in chemistry. This requires knowledge of advanced mathematics and its subsequent transfer to physics' principles in order better understand the chemistry. Use of appropriate scaffolding techniques within and across disciplines was thus necessary to retain student engagement. The students had plenty of opportunity to practise the numeracy and mathematical aspects of the course, both during the lecture with breakout, peer-directed learning style, sessions, and during the problem-solving sessions at the end of a topic.

Sarah had refined her teaching pedagogy based on feedback provided during lecture observations in CHEM243 and on the teaching from the previous semester. Lectures in CHEM243 were clearly structured with a discussion topic stated at the start of each lecture. Students were provided with the aim and direction of the lecture at the start to assist them in their orientation with the program for the duration of the lecture. Problem-solving sessions were structured to enable peer-assisted learning for a small class setting. Students were encouraged to ask questions during lectures to ensure immediate understanding and eliminate lingering confusion about any concepts. Sarah's own question-asking techniques became more open-ended, and frequently involved asking the class whether people wanted to add something to a student statement, or agree or disagree.

These types of techniques were also used by Kennedy et al. (2013) and were quite successful. Trickier concepts were discussed in full at the time and revisited in the tutorial environment to ensure understanding. Verbalising everything written on the board turned out to be a very effective strategy, which also helped to generate rapport with the classroom (which was somewhat unexpected). While Sarah made her notes available prior to the class period, she chose not to do that for worked examples, instead going through those on the board with the entire class. The reason for this was that it is too likely that students read the example and think "yes, I can follow this", incorrectly equating the ability to follow an argument with an understanding of, or having learnt, the material. It also served as an incentive for students to come to class. Indeed, attendance was consistently high during lectures, with typically 85% or more of the students attending.

Sarah made iterative changes to the pedagogy as the teaching progressed, based on the feedback and an increased understanding (by both Sarah and Erik) about the socio-dynamics of the classroom. For example, Sarah used humour in class to lighten the more demanding parts of the application of quantum mechanics to chemistry. This of course is a tried and true pedagogical tactic to build rapport with the classroom. However, for this particular group of students, it fell flat. Something in the socio-dynamics between the students and Sarah made it not work well. As a result, we tried to shift from using humour to a "we are all in this together" approach during the explanations, with Sarah using humour more sporadically and only at points that were more natural rest points in the explanation, worked example or lectures. This approach appeared to work better with students more actively responding to Sarah, and more rapport between Sarah and the students.

Results indicate that students generally had a good grasp of the material. They performed well in the assignment at the mid-point in the semester, which covered all of Sarah's material and was mathematically based. The students also engaged with the material, participating far more in discussion both during and after the lectures than they had done the previous year. Most students coped well with the mathematical questions in the assignment and mistakes were as a result of using incorrect starting values rather than as a result of not understanding the mathematical equations and manipulation of such.

Students benefited from the change in pedagogy and focused attention on the transfer of mathematics to chemistry. Sarah's end-of-semester course evaluations have increased considerably from when she taught CHEM243 last year (i.e. 3.8/5 to 4.4/5). Feedback from the students included:

- Before each class she would outline the learning goals for the lecture.
- She explains concepts and ideas well.
- Loved the way Sarah went step by step and explaining everything. Made everything clear and understandable.
- Would definitely do another paper in which Sarah is teaching more of the course.

For Sarah, engaging in the process of teaching for transfer also provided time to reflect on teaching more generally. She notes that the revisions in teaching style, and the subsequent increased rapport with the students, have made teaching a much more positive experience, both in the 100-, and 200-level courses. The teaching techniques applied in this study have made teaching the material much easier to do as well. For both Sarah and the Department of Chemistry, these positive experiences for students (and staff) will hopefully translate in increased enrolments in (physical) chemistry courses at the 200- and 300-level, and in the number of students interested in doing postgraduate studies in physical chemistry in Sarah's lab.

Discussion and Conclusions

This project reviewed the literature on teaching for transfer and showed the results of implementing the suggestions of the literature into teaching practice. Results show that using these techniques, tailored to the particular level of the students, helped students better perform numeracy and mathematical tasks in chemistry. In addition, students valued these experiences as shown by the increased evaluations scores for the lecturer in this study.

This project underscores the importance of scaffolding while teaching; building upon previous knowledge in visible and structured ways. Sarah’s reflections reveal her realisation that students, as relative novices in the field, think fundamentally differently about the material than she, as the expert. Clear connections between the mathematics and the science need to be made explicit in class, rather than assumed to be understood. To illustrate, one pedagogical strategy that worked well in one of Sarah's last teaching weeks was to "reverse" the lecture. In mathematics and science, there is a tendency to build from first principles, to theory, to application. While this is traditional, and in line with the principles of science and mathematics, it only effectively works as a pedagogical tool when the learner understand where they are going. For students, who do not necessarily see the end-point (the application), ploughing through the principles and theory can be de-motivating. In the reverse model, the lecture starts by showing the application or the process they wish to describe (e.g. being able to find out what the atomic structure of a molecule is). From there, they work backwards via a "what do we need to know and understand to answer this question" model. This creates the motivational hook for the students to engage with the material they would otherwise have considered meaningless.

Overall, the research team conclude that the project has been a successful pilot study. The next step will be to roll the strategies out more broadly across the Faculty of Science. While the focus of this study has been on numeracy and mathematics transfer in chemistry courses, many, if not most of these strategies can easily be adapted to suit particular disciplinary approaches, teaching styles and classroom environments. If one truism could be found in the pedagogy literature, it is this: there is no one correct way of teaching for transfer. Experienced lecturers are likely to share that they often change tactics depending on the class size, the level, and the socio-dynamics, or even the weather! It will be an interesting challenge to scale the project, however. In this pilot, one lecturer was intensively supported by academic developers; such one-on-one support is not a scalable model. The most useful approach could well be for academic developers to work intensively with a few academics, who in turn become "knowledgeable others" (Offerdahl, under review) to assist colleagues in their departments.

Strategic Implications for the College of Science

This project is closely linked to the strategic review of the framework for delivery of science education at the University of Canterbury. Elements of this review include consideration of the diversity and efficiency of ways in which graduates acquire attributes, the appropriateness of attributes, and the way in which the redevelopment of the science facilities will enable new approaches.

The initial research, which showed that students have on paper sufficient mathematical background to cope with the demands of first and second year courses, provided hard data for what until then had been anecdotal evidence, which was not necessarily voiced in a broader Faculty of Science context. The discussion about that research at Faculty of Science meetings brought the issue in sharp focus; comments revealed that several departments were dealing with similar issues, and transfer was identified as a probable cause.

The research mentioned in this report has served as a pilot to help identify beneficial pedagogical strategies and teaching techniques to help students better understand the numeracy and mathematical dimensions underpinning the natural and life sciences.

Both the Pro-Vice-Chancellor and the Dean of Science are strongly supportive of the report, and are planning for the findings of the report to be presented at workshops in the Faculty of Science. The uptake of these professional development-like workshops is expected to be substantial given the findings are from a Faculty initiated project that is ground “in [the Faculty of] Science, with Science, and for Science”.

Earlier in 2013, the BSc was reviewed as part of the regular five-yearly quality assurance framework of the University. Rather than a broad-brush review, the College chose to pick a narrower theme so that more specific, and more actionable, recommendation for change could be made. The focus of the review was on whether the BSc is preparing people for the job market of the future. In the review panel's final report, the "numeracy" projects (both the research in this report and the preceding research that initiated it) were explicitly mentioned, and commended. On page 3 of the report: *“The Panel… commends the working group on numeracy, which is exploring how to ensure that numeracy is a guaranteed competency of each graduate”.*

In the next two years, the Faculty will put considerable effort into examining and updating the graduate profile for the awards offered by Science and reemphasise the importance of clear and measurable learning outcomes for its courses. This project will play a large role in the discussions around numeracy and mathematical ability requirements of BSc graduates (which of course will vary over the majors in the BSc), and how the Faculty can ensure that these requirements are met in its courses through well-formulated learning goals and teaching methods that are informed by the scholarly literature on discipline-based educational research. For the latter objectives the Faculty also intends to use the results from the *Transforming Tertiary Science Education* project (Kennedy et al., 2013), which was done in part by members of the Faculty of Science and funded by Ako Aotearoa.

In addition, it will be worthwhile to examine the transition between secondary and tertiary education in more detail, working with secondary schools to help students see the intimate links between science and mathematics, and the need to approach these subjects integrally, rather than as two separate topics that have no relation with one another.

Effective Numeracy Transfer Good Practice Guide

Effective transfer from one cognitive domain (e.g. mathematics) to another (e.g. science) involves structuring the learning environment and activities in ways that:

- Minimize cognitive load (through learning aids or focused attention).
- Emphasise the value of the learning material and its potential purpose for different contexts/disciplines.
- Meet students where they are at (by identifying prior knowledge, assumptions, aims for their learning, intentions for use of the material learned and designing curriculum that suits).

The following is a list of evidence-based strategies from the literature that support transfer of skills and conceptual understanding from one setting to another:

- Practice. Provide opportunities for students to practice the material in thorough and diverse ways 9Luria, 1976; Scribner & Cole, 1981).
- Worked examples. In a step-by-step fashion, work through the problem solving process in front of students (Atkinson, Derry, Renkl & Wortham, 2000; Grobe & Renkl, 2007).
- Abstraction. Invite students to explore other possible connections with mathematics, or other target subject (see Gick & Holyoak, 1983; Gick & Holyoak, 1980); also referred to as 'bridging' (see Fogarty, Perkins, and Barell, 1992).
- Models and simulations. Use simulations that are characterised by varied appearances (Gick & Holyoak, 1983; Gick & Holyoak, 1980; Goldstone & Son, 2005) and progressive idealization of simulations, or "concreteness fading" (Goldstone & Son, 2005).
- 'Hugging'. Provide learning experiences that simulate the ultimate applications (Fogarty, Perkins, and Barell, 1992).
- Metacognitive reflection. Engage students in the process of actively self-monitoring their approach, process, and outcomes 9Perkins & Solomon, 1992).
- (Student and instructor) Self-verbalisation (de Bruin, Rikers & Schmidt, 2007).
- Conducive classroom climate. Remain mindful of the ways in which activities and environments are conducive to focused learning (minimising distractions and creating 'safe' spaces for success *and* failure). (Perkins & Solomon, 1992).
- Drawing upon students' prior knowledge and experience. Student-generated data or examples (Bernardo, 2001; Woolnough, 2000), or analogical model formulation (Klenk & Forbus, 2009) in which scenario models of everyday

situations are built, based on prior experience may assist in this regard.

- Building communities of practice. Provide ample opportunities for monitored and thoughtfully planned peer-to-peer instruction (Mazur, 1997) and cooperative learning (Kramarski, 2004).

Over the course of two semesters in this study, six specific strategies were implemented. The number of strategies was deliberately kept to a minimum because a manageable number of changes within a fixed time period is more likely to lead to productive and sustained change.

Semester 1 Strategies (First year Introductory Chemistry course)

- Setting clear expectations for what is to be learned, and clearly identify what students will be held accountable for.

- Using worked examples to illustrate how chemistry concepts mirror and/or translate from other known mathematical problems.

- Bridging conceptually between what students know/are coming to know and other applications within and outside of chemistry; clearly verbalising links to prior knowledge and how the current material will be linked and be relevant to future lectures and classes.

- Using analogies to tie content to daily-life experiences of the students.

Semester 2 Strategies (Second year Physical Chemistry course)

- Verbalising while writing lecture notes or equations on the board to both model cognitive approaches and to allow auditory learners better access to the material.

- Facilitating student interactions and discussions; encouraging students to reflect on the process and outcomes of their learning and their work.

References

Atkinson, R., Derry, S., Renkl, A., & Wortham, D. (2000). Learning from examples: Instructional principles from the worked examples research. *Review of Educational Research, 70*(2), 181-214.

Baker, S., Gersten, R., & Lee, D.-S. (2002). A synthesis of empirical research on teaching mathematics to low-achieving students. *The Elementary School Journal, 103*(1), 51-73.

Bassok, M., & Holyoak, K. J. (1989). Interdomain Transfer Between Isomorphic Topics in Algebra and Physics. *Journal of Experimental Psychology. Learning, Memory & Cognition, 15*(1), 153-166.

Bernardo, A. B. I. (2001). Analogical Problem Construction and Transfer in Mathematical Problem Solving. *Educational Psychology, 21*(2), 137-150.

Boaler, J. (1993). Encouraging the transfer of `school' mathematics to the `real world' through the integration of process and content, context and culture. *Educational Studies in Mathematics, 25*(4), 341-373.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (2000). *How people learn: Brain, mind, experience, and school.* Washington, DC: National Academy Press.

Bransford, J., & Schwartz, D. (1999). Rethinking transfer: A simple proposal with multiple implications. In A. Iran-Nejad & P. Pearson (Eds.), *Review of reserach in education* (Vol. 24, pp. 66-100). Washington, D. C.: American Educational Research Association.

Brogt, E. (2012). *Mathematics preparation in the CHEM112 cohort in 2008 – 2010 and the CHEM211 cohort in 2011*. Internal University of Canterbury report.

Carraher, D., & Schliemann, A. D. (2002). The Transfer Dilemma. *Journal of the Learning Sciences, 11*(1), 1-24.

Davis, B., & Sumara, D. J. (2006). *Complexity and education: Inquiries into learning, teaching, and research*. Mahwah, N.J.: Lawrence Erlbaum Associates.

de Bruin, A., Rikers, R., & Schmidt, H. (2007). The effect of self-explanation and prediction on the development of principled understanding of chess in novices. *Contemporary Educational Psychologist, 32*, 188-205.

Dweck, C. S. (1986). Motivational Processes Affecting Learning. *American Psychologist, 41*(10), 1040-1048.

Evans, J. (1999). Building Bridges: Reflections on the problem of transfer of learning in mathematics. *Educational Studies in Mathematics, 39*(1-3), 23-44.

Fogarty, R., Perkins, D., & Barell, J. (1992). *How to Teach for Transfer.* Palatine, Illinois: Skylight Publishing, 1992.

Frade, C., Winbourne, P., & Braga, S. M. (2009). A mathematics-science community of practice: Reconceptualising transfer in terms of crossing boundaries. *For the Learning of Mathematics, 29*(2), 14-22.

Gee, J. (2000). Identity as an analytic lens for research in education. *Review of Research in Education, 25*, 99-125.

Gick, M., & Holyoak, K. (1983). Schema induction and analogical transfer. *Cognitive Psychology, 15*, 1-38.

Gick, M., & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology, 12*, 306-365.

Goldstone, R. L., & Son, J. Y. (2005). The Transfer of Scientific Principles Using Concrete and Idealized Simulations. *Journal of the Learning Sciences, 14*(1), 69-110.

Greeno, J. (1997). On claims that answer the wrong questions. *Educational Researcher, 25*(1), 5-17.

Große, C. S., & Renkl, A. (2007). Finding and fixing errors in worked examples: Can this foster learning outcomes? *Learning & Instruction, 17*(6), 612-634.
Hattie, J. (2009). *Visible learning*. New York: Taylor & Francis.
Hawk, T., & Shah, A. (2007). Using learning style instruments to enhance student learning. *Decision Sciences Journal of Innovative Education, (5),* 1, 1-19.
Hoban, R. A., Finlayson, O. E., & Nolan, B. C. (2013). Transfer in chemistry: a study of students' abilities in transferring mathematical knowledge to chemistry. *International Journal of Mathematical Education in Science & Technology, 44*(1), 14-35.
Jones, J. L., Jones, K. A., & Vermette, P. J. (2009). Teaching mathematics understanding for transfer. *Teaching Mathematics and its applications, 28*, 145-149.
Kennedy, B., Brogt, E., Jordens, Z., Jolley, A., Bradshaw, R., Hartnett, M., O'Steen, B., Hartung, E., Soutter, A., Cartwright, G. and Burr, N. (2013) *Transforming Tertiary Science Education: Improving learning during lectures.* Ako Aotearoa, National Centre for Tertiary Teaching Excellence.
Klenk, M., & Forbus, K. (2009). Analogical model formulation for transfer learning in AP Physics. *Artificial Intelligence, 173*(18), 1615-1638.
Kramarski, B. (2004). Making sense of graphs: does metacognitive instruction make a difference on students' mathematical conceptions and alternative conceptions? *Learning & Instruction, 14*(6), 593-619.
Lave, J. (1993). The practice of learning. In S. Chaiklin & J. Lave (Eds.), *Understanding practice: Perspectives on activity and context*. New York: Cambridge University Press.
Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. New York: Cambridge University Press.
Lobato, J. (2006a). Alternative Perspectives on the Transfer of Learning: History, Issues, and Challenges for Future Research. *Journal of the Learning Sciences, 15*(4), 431-449.
Lobato, J. (2006b). Relationships between Attention-Focusing and the "Transfer" of Learning Across Two Instructional Approaches to Rates of Change. *Conference Papers -- Psychology of Mathematics & Education of North America*, 1.
Lobato, J. (2012). The Actor-Oriented Transfer Perspective and Its Contributions to Educational Research and Practice. *Educational Psychologist, 47*(3), 232-247.
Lobato, J., Rhodehamel, B., & Hohensee, C. (2012). "Noticing" as an Alternative Transfer of Learning Process. *Journal of the Learning Sciences, 21*(3), 433-482.
Luria, A. (1976). *Cognitive development: Its cultural and social foundations*. Cambridge, MA: Harvard University Press.
Mazur, E. (1997). *Peer instruction, a user's manual*. Upper Saddle River, NJ: Prentice Hall.
O'Byrne, J. W., Britton, S., George, A., Franklin, S., & Frey, A. (2009). Using academic predictors to identify first year science students at risk of failing. *CAL-laborate International, 17*(1), 15-25.
Offerdahl, E. (under review). The process of science instructors' reflection: The role of a knowledgeable other.
Perkins, D., & Salomom, G. (1988). Teaching for transfer. *Educational Leadership, 46*(1), 22-32.
Perkins, D., & Salomom, G. (1992). Transfer of learning *International Encyclopedia of Education* (2nd ed.). Oxford: Pergamon Press.
Potgieter, M., Harding, A., & Engelbrecht, J. (2008). Transfer of algebraic and graphical thinking between mathematics and chemistry. *Journal of Research in Science Teaching, 45*(2), 197-218.

Rebello, N. S., Zollman, D. A., Allbaugh, A. R., Engelhardt, P. V., Gray, K. E., Hrepic, Z., & Itza-Ortiz, S. F. (2004). *Dynamic transfer: a perspective from physics education research*. In J.P. Mestre (Ed.) Transfer of Learning: Research and Perspectives. Greenwich: Information Age Publishing.

Redish, E. F. (2003). *A theoretical framework for physics education research: Modeling student thinking*. Paper presented at the International School of Physics "Enrico Fermi", Course CLVI, Varenna, Italy.

Roberts, A. L., Sharma, M. D., Britton, S., & New, P. B. (2009). Identification and use of theoretical frameworks for a qualitative understanding of mathematics transfer. *CAL-laborate International, 17*(1), 1-14.

Robers, A. L., Sharma, M. D., Britton, S., & New, P. B. (2007). An index to measure the ability of first year science students to transfer mathematics. *International Journal of Mathematical Education in Science and Technology, 38*(4), 429-448.

Sampson, K. A., & Brogt, E. (2011). *The mathematics and science secondary pathways for chem112 students*. Internal University of Canterbury. report

Scribner, S., & Cole, M. (1981). *The psychology of literacy*. Cambridge, MA: Harvard University Press.

Wagner, J. F. (2006). Transfer in Pieces. *Cognition & Instruction, 24*(1), 1-71.

Wenger, E. (1998). *Communities of practice: Learning, meaning and identity*. Cambridge: Cambridge University Press.

Woolnough, J. (2000). How do students learn to apply their mathematical knowledge to interpret graphs in physics? *Research in Science Education, 30*(3), 259-267.